Eur Spine J (2010) 19:732–738
DOI 10.1007/s00586-010-1320-2

ORIGINAL ARTICLE

Coronal plane segmental flexibility in thoracic adolescent idiopathic scoliosis assessed by fulcrum-bending radiographs

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Received: 10 August 2009 / Revised: 16 November 2009 / Accepted: 31 January 2010 / Published online: 26 February 2010

Abstract Knowledge about *segmental flexibility* in adolescent idiopathic scoliosis is crucial for a better biomechanical understanding, particularly for the development of fusionless, growth-guiding techniques. Currently, there is lack of data in this field. The objective of this study was, therefore, to compute segmental flexibility indices (standing angle minus corrected angle/standing angle). We compared segmental disc angles in 76 preoperative sets of standing and fulcrum-bending radiographs of thoracic curves (paired, two-tailed t tests, $p < 0.05$). The mean standing Cobb angle was 59.7° (range 41.3°–95°) and the flexibility index of the curve was 48.6% (range 16.6–78.8%). The disc angles showed symmetric periapical distribution with significant decrease (all p values <0.0001) for every cephalad (+) and caudad (−) level change. The periapical levels +1 and −1 wedged at 8.3° and 8.7° (range 3.5°–14.8°), respectively. All angles were significantly smaller on the-bending views (p values <0.0001). We noted mean periapical flexibility indices of 46% (+1), 49% (−1), 57% (+2) and 81% (−2), which were significantly less ($p < 0.001$) than for the group of remote levels 105% (+3), 149% (−3), 231% (+4) and 300% (−4). The discal and bony wedging was 60 and 40%, respectively, and mean values 35° and 24° ($p < 0.0001$). Their relationship with the Cobb angle showed a moderate correlation ($r = 0.56$ and 0.45). Functional, radiographic analysis of idiopathic thoracic scoliosis revealed significant, homogenous segmental tethering confined to four periapical levels. Future research will aim at in vivo segmental measurements in three planes under defined load to provide in-depth data for novel therapeutic strategies.

Keywords Idiopathic scoliosis · Fulcrum-bending views · Segmental stiffness · Segmental flexibility

Introduction

The appreciation of spinal *segmental* flexibilities in adolescent idiopathic scoliosis is crucial for biomechanical understanding, development of novel therapeutic strategies and personalized surgical planning. Clinically applied, emerging or still experimental non-fusion methods, such as convex disc-bridging stapling, disc-sparing physeal plating, flexible tethering of the curve and concave continuous distraction, rely on amendment of progressive forces into a growth-modulation and soft tissue remodelling corrective factor [1–5]. Optimal number and levels of vertebrae to be spanned, as well as direction, level and modus of load application need to be defined for the future guidance of fusionless scoliosis treatment [6].

Astonishingly, there is still complete lack of published data on the *segmental* responses of scoliotic curves to load. Only one study has so far objectified true total curve "flexibility" in the mechanic sense of a defined load–deformation process by applying axial forces via a shoulder harness [7]. However, even without precise information about forces, it is common orthopaedic practice to coin

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data gained from force–deformation tests as “flexibility”. Current preoperative functional assessments of *global* curve flexibility are based on avoidance of axial gravitational forces with the patient supine, manual translational forces, active sideways bending, traction or on bending the patient over a fulcrum [9]. The latter is particularly efficient for the most frequently operated on, moderate thoracic curves (<60°). This information supports the determination of spinal segments to be included in fusion, eases the decision on anterior release and provides data for the evaluation of surgical procedures.

The purpose of this study was to gain insight into segmental mobility of scoliotic thoracic spines by comparing disc wedging in upright and fulcrum-bending radiographs.

Materials and methods

After IRB approval, we retrospectively analysed segmental flexibility in adolescent patients who had undergone thoracic fulcrum-bending views prior to posterior instrumented fusion for idiopathic scoliosis. Inclusion criteria were main curve thoracic vertebral apex, Cobb angle >40° and a full set of standing posteroanterior radiographs of the spine and a fulcrum-bending radiograph as described hereinafter. Structurality of the curve, defined as lack of correctability below 25° [8], was not a prerequisite since we also saw thoracic main curves of more than 40° Cobb angles and associated typical three-dimensional trunk deformities (flattening of the sagittal profile and cosmetically disturbing rib humps of >10°) but with correctability below 25°.

Nomenclature

We excluded curves with a disc as the apex, which accounted for about 10% of all primarily analysed cases. Thus, the disc spaces were labelled with +1 for the first disc space above the apex, +2 for the second, etc. and −1 for the first disc space below the apex, etc.

Wedging angle: +, scoliotic in the same direction; −, reversed to the curve.

Fulcrum-bending technique

We have performed preoperative fulcrum-bending views since its first description by Cheung and Luk [9]. The obliquity of the ribs places the fulcrum caudal of the apex. The latter is determined on the upright radiograph, followed by skin marking of the corresponding rib. The patient is placed in a lateral decubitus position (convex curve side down and contralateral arm stretched over the head) on a padded fulcrum, which provides maximum inclination by avoiding surface contact of the shoulder. The frontal plane needs to be aligned to the cassette. Since most patients have a flat sagittal profile, the intervertebral spaces are fully visible. Blurred X-rays with uncertain landmarks or with misplaced fulcrums were excluded.

Assessment of curve flexibility

All radiographs were digitally analysed (Software: AxioVision Rel.4.4 Carl Zeiss, Jena/Germany) by an experienced spine surgeon (CH). The Cobb angle of the thoracic curve was assessed between the most inclined vertebrae by marking parallel lines to the upper endplate of the upper end vertebra and the lower endplate of the lower end vertebra on both the upright and the bending view. The levels of the end vertebrae changed since the curve usually included fewer segments on the bending view. The following equation was used for the flexibility of the curve:

$$\begin{aligned}&\text{Curve flexibility index}(\%)\\&= (\text{upright Cobb angle} - \text{bending Cobb angle})\\&\quad\times 100/\text{upright Cobb angle}\end{aligned}$$

Assessment of segmental flexibility (Fig. 1)

Disc angle was measured between straight lines along the inferior endplate of the upper and the superior endplate of the lower vertebra in a segment. This was done on the upright and bending radiographs, including segments as defined by the upright curve. The following equation was used for the segmental flexibility:

$$\begin{aligned}&\text{Segmental flexibility index }(\%)\\&= (\text{upright disc angle} - \text{bending disc angle})\\&\quad\times 100/\text{upright disc angle}\end{aligned}$$

Vertebral wedging

The total extent of bony deformity was calculated by deducting the sum of the disc angles from the upright Cobb angle.

Statistical analysis

All statistical analyses were performed by one of the authors (PB) using SAS 9.2 (SAS Institute, Cary/USA). Segmental correctability at the different levels was tested. To correct for multiple significance tests, the calculated p values were adjusted using Tukey’s technique. It ensures that the chance of finding a significant difference in any comparison (under a null model) is maintained at the alpha level of the test, thus preserving family-wise type I (or false positive) error. T tests (paired, two-tailed) were used to compare distribution of the variable when the results were

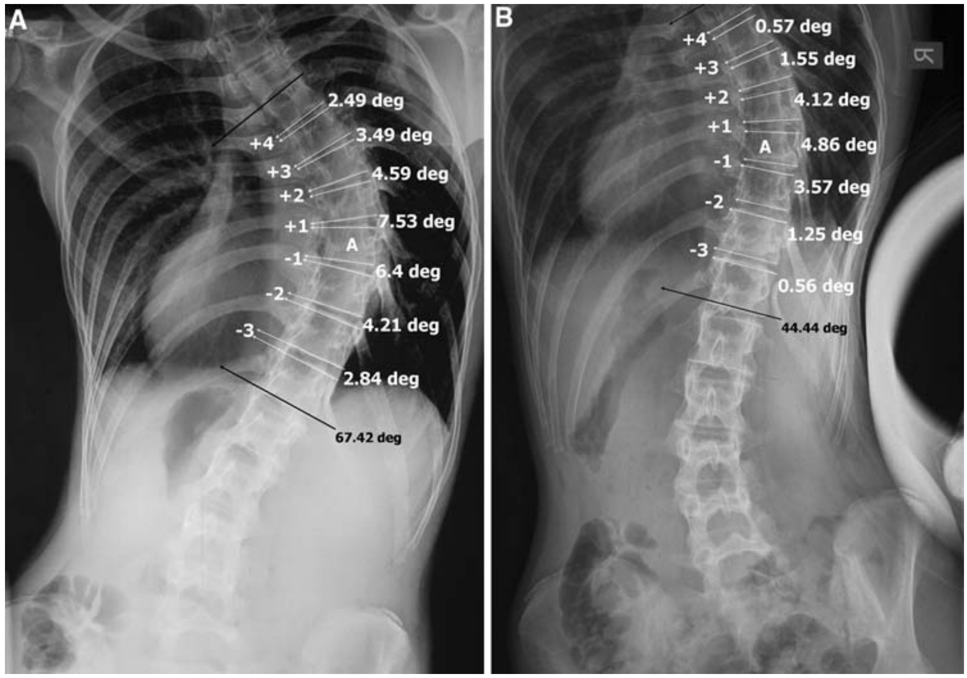

Fig. 1 A 16-year-old girl with right thoracic adolescent idiopathic scoliosis (67° Cobb angle, apex T9). Standing posterior–anterior radiograph (*left*) and fulcrum-bending view (*right*) with segmental measurements of disc wedging

sorted into two groups. Statistical significance was defined as $p < 0.05$. Linear regressions were calculated separately for the bone and disc angulations relative to the Cobb angle.

Intraobserver reliability

Ten randomly chosen sets of radiographs (standing posterior–anterior, fulcrum-bending radiograph) were analysed by the author (CH): wedging of the two periapical discs and the two discs at the upper and lower end of the curve were measured twice at a 1-year interval. Intraobserver reliability was expressed as Pearson's correlation coefficient for disc angle measurements and segmental flexibilities. We considered values of 0.0–0.25 as absent or poor, 0.25–0.49 as low, 0.50–0.69 as fair/moderate, 0.70–0.89 as good and 0.90–1.0 as excellent correlation [10].

Results

We retrieved 111 complete sets of radiographs, of which 35 did not meet all inclusion criteria or were of insufficient quality. The resulting 76 were analysed. These were from 13 boys and 63 girls with an average age of 14.9 years ± 1.8 (range 11–20 years).

Curve characteristics on the standing radiograph

We noted a mean Cobb angle of 59.7° ± standard deviation 12.9 (range 41.3°–95°). T8 (36) and T9 (22) were the most common apex levels, along with T7 (8), T10 (7), T5 (2) and T6 (1). The average number of discs involved in the curve was 6.4 (range 5–8), with an equal number of 3.2 below and above the apex (range 2–5) ($p = 0.5287$).

Curve characteristics on the fulcrum-bending radiograph

The mean Cobb angle was 31.4° ± 12.7 (range 9.1°–60.8°) and flexibility index 48.6 ± 14.3% (range 16.6–78.8%). Fulcrum-bending angles were smaller than the standing Cobb angles ($p < 0.0001$).

Cobb angles were ≤60° in 46 and >60° in 30 patients: average flexibility indices were 53 ± 12.8% (range 17–79%) and 42 ± 14.6% (range 21–73%), respectively ($p = 0.0004$). We found very flexible curves (fulcrum-bending angles <25°) in 13/46 patients with curves ≤60° and in 1/30 with curves >60°.

The average number of discs involved was 4.2 (range 2–6), and those below and above the apex were 1.9 (range 0–3) and 2.3 ± 0.9 (range 0–4), respectively ($p = 0.0039$).

Comparison between standing and fulcrum-bending views

The standing Cobb angle was higher ($p < 0.0001$). The number of involved discs was higher in the standing radiograph ($p < 0.0001$) and that above as well as below the apex significantly higher in the standing radiograph (both $p < 0.0001$).

Table 1 Segmental disc wedging and flexibilty

Disc level[a]	No of discs	Standing angle[b]		Bending angle[b]	Flexibility index (%)
+5	1	0.2° ± 0.0		−1.4° ± 0.0	
+4	18	1.7° ± 1.3 (range −0.9 to 4.1°)	$p < 0.0001$	−1.6° ± 2.2 (range −6.3 to 1.5°)	231 ± 193
		$p < 0.0001$		$p = 0.00013$	
+3	71	3.2° ± 1.9 (range −0.3 to 7.5°)	$p < 0.0001$	0.1° ± 1.9 (range −4.5 to 3.4°)	105 ± 139
		$p < 0.0001$		$p < 0.0001$	
+2	76	5.3° ± 2.0 (range 0.9 to 11.1°)	$p < 0.0001$	2.4° ± 1.6 (range −1.4 to 6.1°)	57 ± 31
		$p < 0.0001$		$p < 0.0001$	
+1	76	8.3° ± 2.4 (range 3.5 to 14.8°)	$p < 0.0001$	4.5° ± 2.2 (range −0.6 to 9.9°)	46 ± 22
Apex					
−1	76	8.7° ± 2.7 (range 3.5 to 14.8°)	$p < 0.0001$	4.5° ± 2.6 (range −1.8 to 13.7°)	49 ± 24
		$p < 0.0001$		$p < 0.0001$	
−2	76	6.1° ± 2.2 (range 1.5 to 13.2°)	$p < 0.0001$	1.5° ± 2.1 (range −6.6 to 5.4°)	81 ± 42
		$p < 0.0001$		$p < 0.0001$	
−3	69	3.3° ± 1.5 (range −6.9 to 7.4°)	$p < 0.0001$	−1.5° ± 2.6 (range −9.1 to 3.5°)	149 ± 228
		$p < 0.0001$		$p < 0.0001$	
−4	18	1.5° ± 1.2 (range −11 to 3.9°)	$p < 0.0001$	−3.4° ± 1.7 (range −7.5 to 0.4°)	300 ± 436
−5	2	2.5° ± 1.1		−4.7° ± 1.3	

− means reverse angle correction

Group comparison with two-tailed paired t test, significance level $p = 0.005$

[a] + above/− below apex

[b] Average disc angle ± standard deviation

Segmental disc angles

Detailed data are given in Table 1. Every step upwards and downwards from the apex decreased the disc angle significantly (all p values < 0.00015) in the standing and bending views. At every level, the values were significantly smaller on the bending views (all p values <0.0001). Only the angles of the four periapical discs showed scoliotic wedging on the bending views.

Segmental flexibility indices are shown in Fig. 2 and Table 1. The levels close to the apex (−2 to +2) had a similar extent of limited correctability. This group was stiffer than the one including all distant levels ($p < 0.001$). Correctability above and below the apex was not different ($p = 0.07$) though the average correction was higher for the levels −4 to −1 than for +1 to +4 (145 and 109%, respectively).

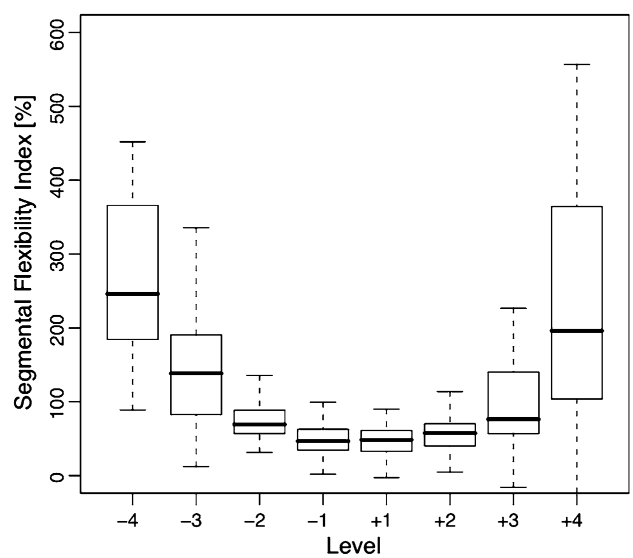

Fig. 2 Segmental flexibility indices in relation to disc level

Bony deformity

The average sum of vertebral wedging was 24° ± 9 (range 7°–42°) and of disc angles 35° ± 9 (range 9°–59°) ($p < 0.0001$). This corresponds to an average of 3.7° bony wedging per vertebra (average 6.41 segments/curve). We noted a mean relative bony and discal wedging of 40% (range 12–64%) and 60% (range 12–87%), respectively ($p < 0.0001$). Curves ≤60° had significant smaller *absolute* values of bony deformities than curves >60° ($p < 0.0001$). The *relative* contribution of the bone deformity to the total deformity was *not* higher in bigger curves ($p = 0.27371$) (Fig. 3).

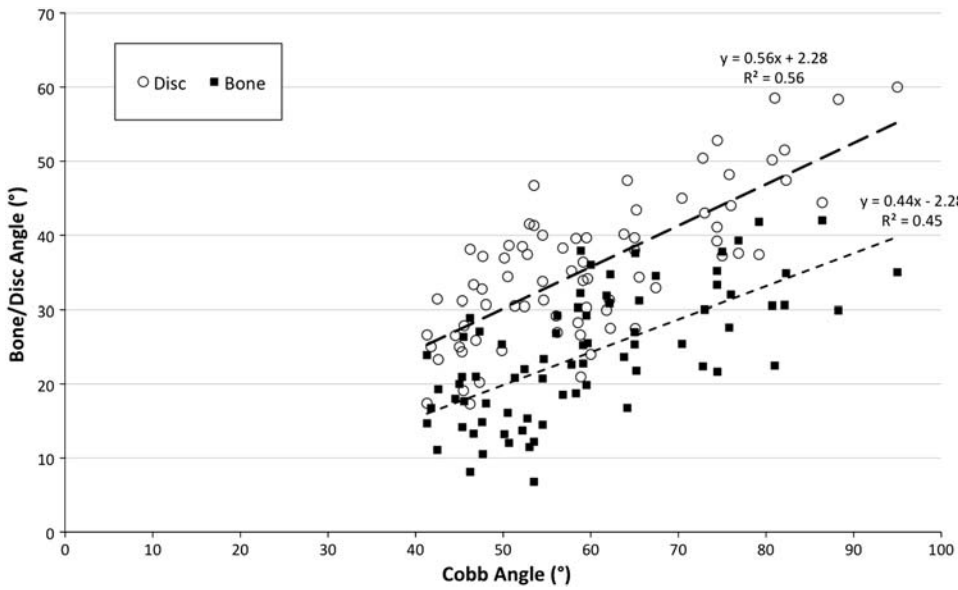

Fig. 3 Total bony and discal deformity in relation to Cobb angle

Table 2 Intraobserver analysis of manual disc wedging measurement and segmental flexibility index

	Disc wedging			Segmental flexibility index[a]		
	Apical	Curve ends	All	Apical	Curve ends	All
Standing radiograph	0.80	0.74	0.92	–	–	–
Bending radiograph	0.93	0.93	0.93	–	–	–
All radiographs	0.92	0.88	0.93	0.87	0.52	0.57

Data are presented as intraclass correlation coefficient r

[a] Segmental flexibility index (%) = (upright disc angle − bending disc angle) × 100/upright disc angle

Intraobserver reliability

Detailed data are given in Table 2.

All disc angle measurement yielded good to excellent values. Segmental flexibility, which includes computation with two disc measurements, shows moderate correlation at the end of the curve and good correlation around the apex.

Discussion

The mechanical function of the spine is the summation of the behaviour of its individual motion segments. Segmental flexibility is the key parameter of biomechanical analysis and decisive for the development and planning of surgical procedures [7, 11].

We are on the verge of introducing fusionless, growth-modulating methods for scoliosis correction. It is mandatory to gain data about the segmental *stiffness* (relation between load and deformation) of the scoliotic spinal segments. Stiffness reflects a complex, coupled three-dimensional rotatory and translatory response of two adjacent vertebrae to forces. It is governed by the mechano-biologic properties of the intervertebral disc, ligaments, capsules of the facet joints and morphology of vertebrae and rib cage. Currently, there is complete lack of knowledge about segmental behaviour in paediatric scoliotic deformities. The gold standard of biomechanical testing (in vitro on spine machines) fails since paediatric scoliotic cadaver spines are not available, does not include the rib cage and muscle activity and does not reflect a real patient's biomechanics in need of a tailored therapeutic approach. A recently published *scoliosis finite element model* explores the effect of different soft tissue properties on the results of fulcrum-bending tests. However, the model is as usual fed by in vitro data of adult disc properties and does not include intersegmental differences as anticipated for scoliosis [12]. The same applies for the "Spine Surgery Simulator" a new preoperative planning tool based on a biomechanical model and a graphical interface [13].

In an attempt to gain basic biomechanical insights into in vivo *segmental* behaviour of idiopathic thoracic scoliosis, we have compared intervertebral angles of fulcrum-bending and upright radiographs. Such testing, though in an ideal natural environment on an awake patient with a true deformity, is an approximation to real biomechanical evaluation of segmental stiffness: although all segments are exposed to the same forces, their amount and precise direction remain obscure, the assessment is monoplanar and there is no axial preload. Nevertheless, standardized fulcrum-bending technique and analysis of defined subgroups of patients, e.g. right thoracic curves with vertebral apices in this study, still allow conclusions on the relative correctability of different scoliotic segments.

Curve characteristics

For main thoracic curves, as used in our series, fulcrum-bending views are most effective [9, 14, 15]. They predict correctability for both anterior and posterior instrumented fusion [9, 16], since they are based on reproducible, passive forces: the upright and bending angles of our study population of average 59.7° and 31.4°, respectively, were comparable to other series with averages of 51°–58° and 20.4°–24°, respectively [9, 16]. The higher proportion of stiffer deformities (>60°) explains the overall lower correctability in our series. For their assessment, preoperative traction films under general anaesthesia with the patient supine are recommended [17–20]. Only one study measured in an upright position with the awake patients in a harness suspended off the ground [7]. The proportion of curves >60° was lower (11 vs. 30 patients) than in our study and the average Cobb angle higher (77° vs. 71°, $p = 0.01$), but the flexibility index was significantly smaller (32 vs. 42% ($p < 0.0001$). Flexibility was found to decrease by 10% for every 10° increase in curve [21], which renders our bending test as effective as traction in the group of severe curves.

Segmental angles and reducibility

The measurement of *disc angles* was rated good to excellent for intra- (0.89–0.95) and interobserver reliability (0.82–0.97) [10, 22]. We observed similar results for intraobserver reliability (0.74–0.93) of isolated disc measurement and periapical segmental flexibility indices, but only moderate correlation for flexibility at the curve ends (0.52). The latter may be attributed to the small numbers [10]. Axial rotation and sagittal tilting may alter the apparent discal wedging seen in the frontal plane. This is a negligible factor since scoliotic spines usually show a flat profile without sagittal vertebral wedging and tilting [23]. Naturally, the disc angles were small, but within a narrow range compared to other studies [22, 23] The average wedging of four periapical discs was measured at 5.8° in 27 patients with an average of 42.3° idiopathic scoliosis [23]. Longitudinal survey showed that the relative amount of total disc wedging remained stable with curve progression. Accordingly, this allows a linear adjustment to the bigger Cobb angle in our study (59.7°), which yields a corrected disc angle of 7.1°. This corresponds precisely to the average of the four periapical discs in our study. To our knowledge, this is the first report on measurements of disc angles more than two segments remote from the apex. These values diminish significantly and symmetrically caudad and cephalad to the apex with every level. At the ends of the curve, bending of these small angled discs cause high percentages of correction with large standard deviations.

The average *flexibility indices* of the four periapical discs (69%) are significantly less than that of the remote discs, which on an average bend more than 20% reverse to the concavity. The main tether is obviously concentrated in those four central "sick" segments, which also reveal abnormally high intradiscal pressures with intraoperative measurements [24]. The average of 4.2 ± 1.2 discs involved in the scoliotic section of the bending view and significantly less correctability of the four periapical discs also match well with the number of discs commonly resected in anterior release procedures [25]. However, four discs are significantly less ($p < 0.0001$) than the number of discs within an uncorrected curve or an instrumented fusion [17]. Awareness of the pattern of segmental reducibility might influence the choice of levels and the direction of forces for new, corrective strategies. However, since scoliosis is a complex three-dimensional deformity and our analysis is confined to the coronal plane, we caution against drawing simplified conclusions.

Vertebral and intervertebral deformity

For the induction of remodelling, knowledge of discal and bony wedging is relevant. The relative contribution of vertebral and disc wedging was similar in moderate (≤60°) and big (>60°) curves ($p = 0.273$). This supports the statement that both discs and vertebrae develop an increasing deformity in similar proportions with curve progression [23]. In contrast to other authors, we found a higher proportion of disc wedging ($p < 0.0001$) as usually attributed to lumbar deformities [22, 23]. In accordance with other authors, the relationship between Cobb angle/total disc wedging and Cobb angle/total bony deformity showed a moderate correlation ($r = 0.56$ and 0.45, respectively) [22] (Fig. 3). Interindividual differences in bone density and connective tissue properties are possible reasons.

Conclusion

The analysis of segmental correctability on fulcrum-bending views revealed almost homogenous "structural" tethering within the four periapical, scoliotic segments, which were discriminated from more mobile segments towards the end of the curve. Hitherto, the term “structurality” has defined the behaviour of a scoliotic curve in the frontal plane under non-standardized and unquantified loads on side bending [8]. This nomenclature reflects the need of adding functional data to the very limited, static information gathered from standing radiographs to improve the decision-making process and preoperative planning. However, this global approach to scoliosis does not appreciate the functionality of the individual motion units. This study is a first step to break the term “structurality” down to a segmental level. This knowledge will also help to calculate more realistic finite element models of scoliosis. Future research should aim at in vivo *three-dimensional* measurement of segmental rotational and translatory responses to define loads in order to compute the flexibility of the scoliotic motion units, which is inevitable for a better understanding of the biomechanics of scoliosis.

Conflict of interest statement No funds were received in support of this study. No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

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